An FMC-Equipped Aerial Mapping Camera

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ABSTRACT: Forward motion compensation is accomplished by shifting the aerial film in the magazine linearly in the flight direction during film exposure. It ensures collineation of terrain point, center of projection, and image point during the duration of exposure. Forward motion compensation for all points in flat horizontal terrain allows a significant lengthening of exposure time. In the case of terrain height differences, forward motion can be fully compensated only for an average horizontal terrain height; however, a remarkable reduction in forward motion effects is evident, resulting in a significant improvement in image quality. The longer exposure times made possible through the use of forward motion compensation in the LMK aerial camera increase the illumination potential several times over that of ordinary aerial mapping cameras. This feature allows not only the use of aerial emulsions of lower speed and higher resolution, but also photography under poor terrain illumination and from faster aircraft in low-altitude flights. The fiducial marks are exposed precisely at the midpoint between opening and closing of the shutter.

INTRODUCTION

THE AUTHOR PUBLISHED some 30 years ago his first article on forward motion control in aerial mapping cameras (Schöler, 1953). However, the concept then proposed could not be implemented until suitable microprocessors became available in the early 1980s. The experience gained in the last few years with such a camera system fully verifies the expectations formulated three decades ago. Voss and Zeth (1983a, 1983b, 1983c) gave detailed descriptions of such a new aerial camera system with forward motion compensation, designated LMK, and reported results obtained during the first test flights with this camera.

PERFORMANCE OF AERIAL MAPPING CAMERAS

Conventional aerial mapping cameras not equipped with forward motion compensation (FMC) will, in this paper, be referred to as "rigid cameras." Such cameras are usually calibrated in a laboratory under stationary conditions. Commission I of the International Society for Photogrammetry and Remote Sensing (ISPRS) recommended the execution of performance tests under conditions emulating those during the practical use of aerial mapping cameras (Carman, 1960). However, either vertical fan collimators with photographic recording or visual horizontal or vertical goniometers are used, so that a remarkable procedural difference exists between the execution of performance tests in the laboratory on the one hand and the practical application of an aerial camera on the other (Würtz, 1966).

An aerial mapping camera equipped with forward motion compensation will in this paper be referred to as a "dynamically operating camera." Provided that no other image motion effects are present, such a camera keeps terrain point, center of projection, and image point exactly on a straight line during the duration of the exposure, thus avoiding blurring of the image point and allowing a remarkable extension of the exposure time.

Until now it has been generally believed that a significant improvement in image quality is possible only through advances in optical systems and emulsions. However, our experiments with a "dynamically operating camera" have shown that great advances can be achieved using present optical systems and photographic emulsions.

The functions of the new LMK aerial mapping camera will be summarized briefly (Voss and Zeth, 1983a, 1983c). Figure 1 shows the entire LMK system, consisting of the camera and an optical control unit which includes an optical image forming system. During the photographic flight the operator views on the frosted glass screen of the optical control unit a traveling grid which he synchronizes with the moving terrain image. The terrain image moves across the photographic emulsion in the aerial camera magazine during the exposure period in the same way.

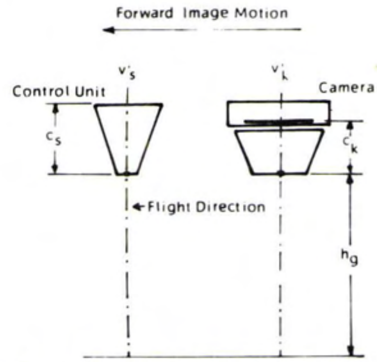

FIG. 1. Aerial camera system for taking overlapping photographs.

The velocities of the image movement v'_s on the viewing screen of the control unit and v'_c on the photographic emulsion are related by the equation

$$\frac{v'_s}{v'_c} = \frac{f_s}{f_c} \tag{1}$$

where f_s and f_c are the (calibrated) focal distances of the control unit (s) and the aerial camera (c), respectively.

In "rigid cameras," blurring of the optical image can be limited to an acceptable amount only by shortening the exposure time, which necessarily involves the requirement to increase the light intensity by enlarging the effective aperture. The same requirement also results from frequently desired narrowing of the spectral range used for the image forming process and from increased flight velocities. Examples are infrared photography and increasingly used multispectral photographic techniques. Consequently, in practical aerial photography, the necessary intensity of light needed to generate a photographic image is only available over a short period of the day during certain seasons of the year.

These important shortcomings of the conventional "rigid camera" have been significantly reduced in the new "dynamically operating" LMK aerial mapping camera. Terrain point, center of projection, and image point are located exactly on a straight line during the entire duration of the exposure, provided that image motion caused by factors other than aircraft forward motion is not present. In general, image motion resulting from aircraft forward motion is significantly larger than that resulting from camera vibration caused by angular camera oscillations, provided that the camera mount ensures adequate damping, that the camera is installed in a suitable place within the aircraft, and that the meteorological conditions during the photographic mission allow for smooth aircraft movement. The aircraft movement becomes even smoother as a result of the

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increased flying speed enabled by the availability of the forward motion compensation, which permits an extension of the exposure time.

PERFORMANCE EVALUATION OF THE LMK AERIAL MAPPING CAMERA SYSTEM

Higher photo-flight veolcities (which also contribute to a more stable attitude of the camera) and a remarkable prolongation of exposure times depend on the following technical parameters of a "dynamically operating camera":

- Forward motion compensation by moving the aerial film during exposure,
- Maximum speed of the traveling grid in the navigation telescope or on the viewing screen of the control unit, and
- Camera cycle.

Particular benefits resulting from the inclusion of forward motion compensation into an aerial mapping camera system are

- larger photo scales,
- lower flying heights, and
- higher flying speeds.

The relation between the first and second parameter listed above is given by Equation 1. Considering the technical data of the LMK system with

$v_{s\ max}$ = maximum speed of the traveling grid in the control unit (30 mm/s);

$v'_{c\ max}$ = maximum film forward motion compensation (32 mm/s); and

ct_{min} = shortest camera cycle 1.6 seconds (1/500 seconds, emulsion speed 650 ASA or 29 DIN) to 4.5 seconds (1/30 seconds, emulsion speed 4 ASA or 6 DIN).

remarkable results are obtained for the practice of aerial photography. The results shown in Figure 2 indicate that a much higher intensity of illumination can be utilized to generate the photogrammetric image. Related to the same *f*-stop as a conventional "rigid camera," about 50 times more energy is available on the image plane.

Hence, the LMK aerial mapping camera can be used with smaller apertures, which permits the construction of lighter lenses. Another possibility is the utilization of aerial film emulsions with lower speed and improved resolving power. In the experimental work done thus far, an effective photographic resolution of approximately 50 lp/mm was achieved, which is better by nearly 30 percent than the best results of conventional "rigid cameras" (Figures 3, 4 and 5).

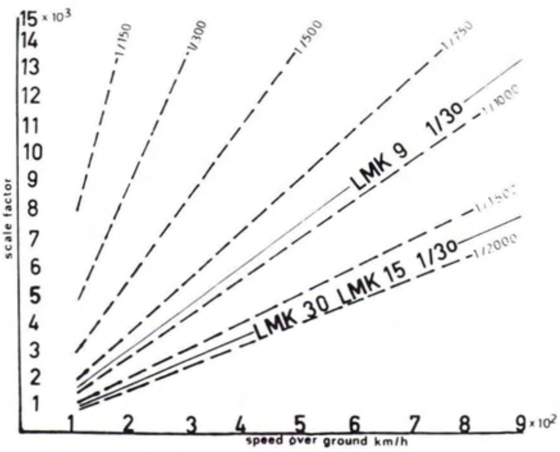


FIG. 2. Comparison of exposure times between a "rigid camera" and the LMK for flat terrain (assumed maximum theoretical image motion for the "rigid camera," 20 μm).

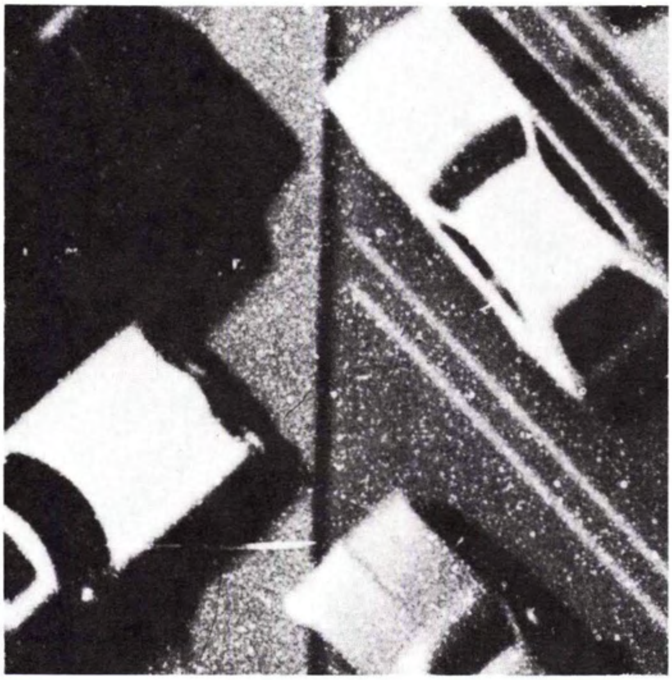
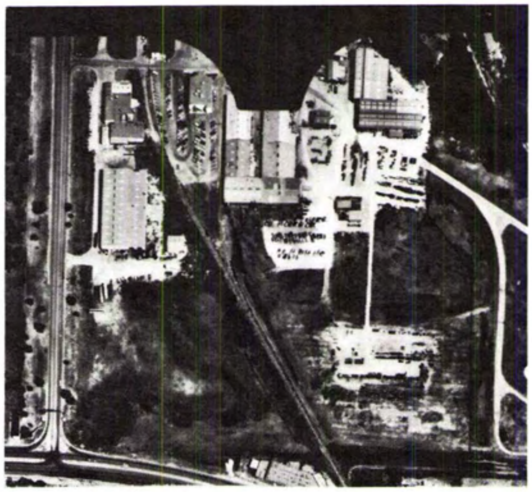


FIG. 3. 75× sectional enlargement of an LMK-photograph taken originally at a scale of 1 : 7170 using a shutter speed of 1/70 seconds and Kodak High Definition Aerial Film 3414. The amount of (calculated) image motion at the enlarged scale is 10.6 mm in the east-west direction.

INFLUENCE OF TERRAIN ELEVATION DIFFERENCES

Flat horizontal terrain was assumed in the preceeding discussion, and the amount of image movement as a function of the photo scale was assumed the same for all terrain points. It seems plausible that points in hilly terrain below or above an average horizontal reference plane must have different amounts of image movement during the duration of the exposure. A terrain point at a shorter distance from the projection center will be imaged at a larger photo scale and will, therefore, be subject to faster image movement in the focal plane of the aerial camera. Thus, differential image movements are caused in the focal plane of the aerial camera by terrain height differences in the flight direction, or opposite to it, depending on whether the respective terrain point lies above or below an average reference plane, for which the image motion was exactly compensated.

The geometric relations are shown in Figure 6. Let us assume



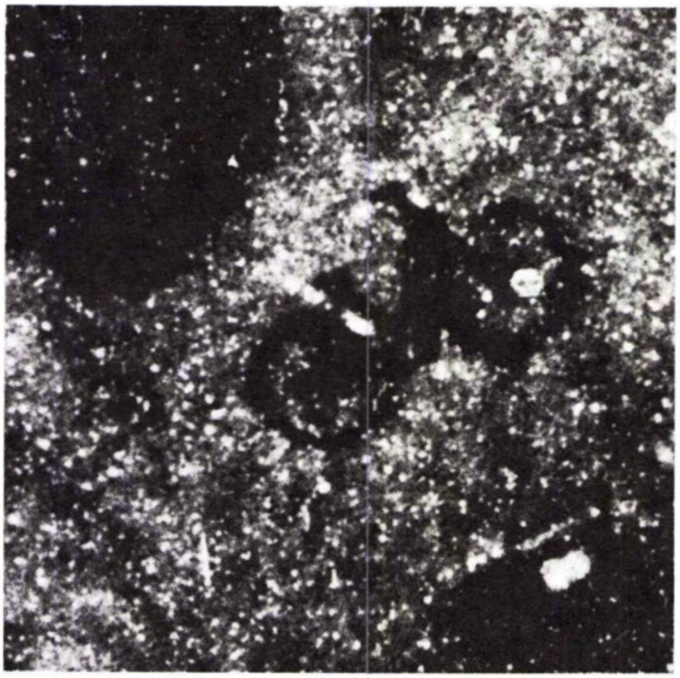


FIG. 4. 100× sectional enlargement of an LMK-photograph taken originally at a scale of 1 : 3550 using a shutter speed of 1/400 seconds and Kodak Panatomic-X Film 2412. The amount of (calculated) image motion at the enlarged scale is 4.3 mm in the east-west direction.

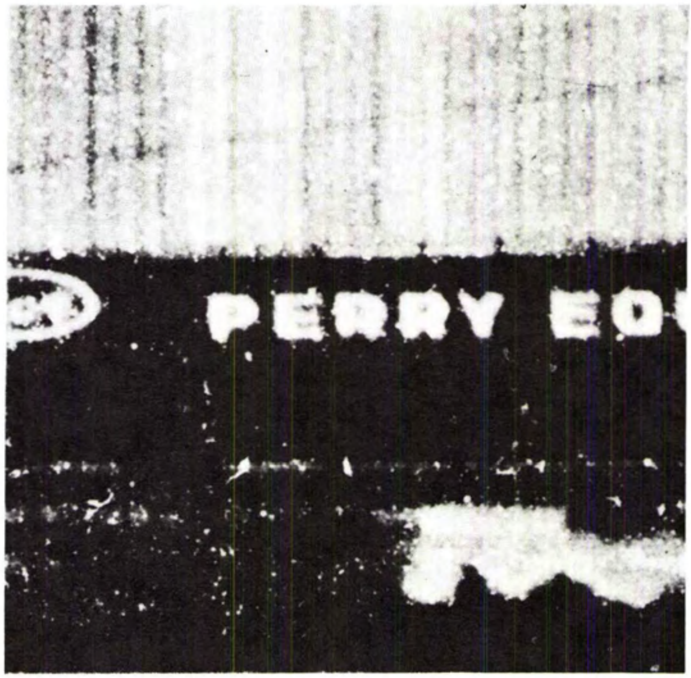


FIG. 5. 50× sectional enlargement of an LMK-photograph taken originally at a scale of 1 : 3680 using a shutter speed of 1/165 seconds and Kodak Panatomic-X Aerographic II film 2412. The amount of (calculated) image motion at the enlarged scale is 5mm in the east-west direction.

a mean flying height over ground h_g and a terrain elevation $\pm\Delta H = \pm x \cdot h_g$. As is evident from Figure 6, the image point P'_V of a terrain point P_V, being nearest to the projection center, is subjected to the fastest speed in the image plane by forward movement of the aircraft at speed v_g during the duration of the exposure. The behavior of point P'_V can be described by equation

$$\overline{P'_V H'} = v_g \cdot \frac{f_c}{h_g - x \cdot h_g} \cdot dt \qquad (2)$$

where dt is the exposure time.

Part of this amount of image movement, namely that with respect to the average horizontal flat terrain, is compensated for by the forward motion compensation

$$\overline{P'_M H'} = v_g \cdot \frac{f_c}{h_g} \cdot dt. \qquad (3)$$

Hence, the image point P'_V theoretically travels during the duration of the exposure an uncorrected distance given by

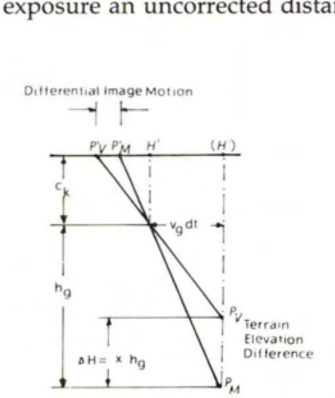


FIG. 6. Differential image motion caused by terrain elevation differences.

$$\overline{P'_V P'_M} = \overline{P'_V H'} - \overline{P'_M H''}$$
$$= (v_g \cdot \frac{f_c}{h_g - x \cdot h_g} - v_g \cdot \frac{f_c}{h_g} dt = \frac{v_g f_c}{h_g} \cdot \frac{x}{1 - x} \cdot dt. \quad (4)$$

Expressed in terms of the duration of the exposure,

$$dt = \frac{h_g}{v_g f_c} \cdot \frac{1 - x}{x} \cdot \overline{P'_V P'_M}$$
$$= m_b \cdot \frac{\overline{P'_V P'_M}}{v_g} \cdot \frac{1 - x}{x} \quad (5)$$

Figure 7 compares, analogously to Figure 2, the conventional "rigid camera" with the LMK aerial mapping camera and again exhibits the considerable gain in light intensity usable by the FMC-equipped LMK camera if the same image motion tolerance of 20 μm in the image plane is assumed for both camera types.

Experience shows that calculated amounts of image motion become apparent in the photograph only in a magnitude of 20 to 50 percent of the resolved distance of the lens/film combination being used. A hypothetical model explaining this fact is presented in Figure 8. The photographic emulsion consists of very small grains of silver halide embedded in a gelatine layer. They are assumed to be much smaller than a light spot coming from an object detail and entering the emulsion. Any movement between the object and the camera consequently also causes the light spot to be moved acrosss the emulsion surface, as is shown in Figure 8. In such a case not all of the emulsion grains receive the same amount of energy. Only in the central image area is there sufficient beam intensity to generate a latent image in the emulsion.

Therefore, the effective image motion is smaller than the calculated amount. The magnitude of this difference also depends on the emulsion type and the photochemical processing. During the restitution process the operator will always set the measuring mark of the plotting machine to the center point of the blurred image. Thus, the distance between this center point (Figure 9) and the fully compensated image point P' is

$$\frac{\overline{P'_V P'_M}}{2} = \frac{1}{2} + \frac{v_g f_c}{h_g} \cdot \frac{x}{1 - x} \cdot dt = a. \quad (6)$$

According to Figure 9 and Equation 6,

$$m' = m \cdot \frac{f_c}{h_g} \text{ and } m' + a = \frac{f_c}{h_g - x\, h_g} \cdot m \quad (7)$$

so that

$$m = \frac{1}{2} \cdot v_g \cdot d_t \quad (8)$$

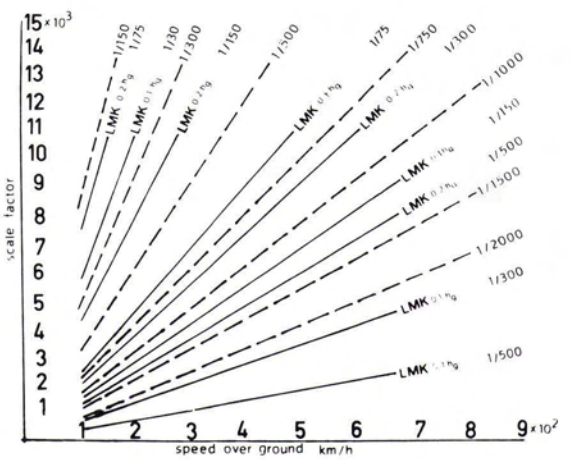


FIG. 7. Comparison of exposure times for a "rigid camera" and the LMK camera in the presence of terrain elevation differences ΔH (assumed maximum image motion, 20 μm).

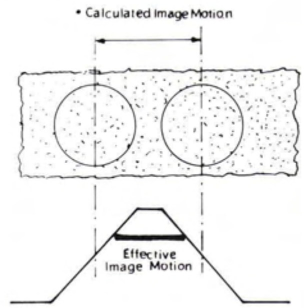


FIG. 8. Hypothetical model of effective image motion.

This means that through the effect of image motion compensation we finally obtain a central-perspective photograph with the projection center (0) instead of a fixed photograph with the projection center 0, taken with a conventional "rigid camera."

Care must be taken to position the fiducial marks in the image plane in such a way that the point of intersection of the lines joining them represents the projection center (0) exactly. The fiducial marks must be exposed precisely at the midpoint of the exposure of the aerial photograph to realize the stated requirement.

The geometry of a "dynamically operating camera" depends sensitively on the well-timed exposure of the fiducial marks. A ± 10 μm deviation of the principal point from its theoretical position is generally tolerated for high-precision mapping cameras. Certain time tolerances apply for exposing the fiducial marks at the midpoint of the shutter opening time with different film movement for image motion compensation. These are shown in Table 1 based on Equation 8.

EXAMPLE OF APPLICATION

Assume that a final map at a scale of 1 : 2 000 is required. As a result of the improved image quality offered by the LMK aerial mapping camera, a photo scale can be selected about 30 percent smaller than that for a "rigid camera." Instead of a previously used photo scale 1 : 6 000, a scale of approximately 1 : 7 800 is now acceptable. This means that only 77 percent of the photographs required previously to cover a single strip of the terrain are needed when taken with the LMK, and that only 59 percent of previously required photographs are required to cover the same area. A wide angle camera with a focal length of 152 mm will produce photographs at the scale of 1 : 7 800 when flown 1 200 m above ground.

Film movement of 28 mm/s in the magazine during exposure permits an increased flying speed of 800 km/h. With terrain

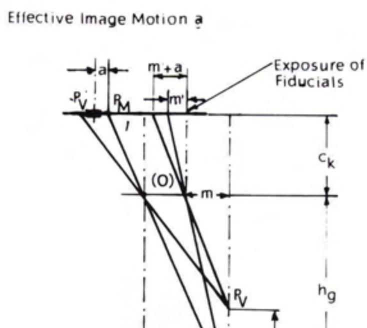


FIG. 9. Image motion geometry for the LMK camera.

Table 1. Tolerances for Fiducial Mark Exposure in Relation to Compensation Velocities

Forward Motion Compensation (mm/s)	30	25	20	15	10	5	2
Tolerance for Fiducial Mark Exposure (ms)	0.33	0.4	0.5	0.67	1.0	2.0	5.0

elevation differences reaching 10 percent of the average flying height above ground, an exposure time of 1/300 seconds can be accepted. The LMK aerial mapping camera has a time regime for the camera cycle which guarantees the exposure of the fiducial marks at the midpoint of photo exposure with an accuracy of 1 percent of the exposure time. The resulting deviation of the principal point of 0.9 μm can be neglected. For taking photographs with a conventional "rigid camera" at a scale of 1 : 6 000 and a flying speed over ground of 350 km/h, the exposure time must be at least 1/1 000 s. This example demonstrates clearly the remarkable performance potential of an aerial surveying camera with an image motion control device.

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